# Production and energy loss of strange and heavy quarks

**Lijuan Ruan (for the STAR Collaboration)**

Physics Department, Brookhaven National Laboratory, Upton, New York, NY 11973, USA

E-mail: `ruanlj@rcf.rhic.bnl.gov`

**Abstract.**

Data taken over the last several years have demonstrated that RHIC has created a hot, dense medium with partonic degrees of freedom. Identified particle spectra at high transverse momentum ($p_T$) and heavy flavor are thought to be well calibrated probes thus serve as ideal tools to study the properties of the medium. We present $p_T$ distributions of particle ratios in p+p collisions from STAR experiment to understand the particle production mechanisms. These measurements will also constrain fragmentation functions in hadron-hardon collisions. In heavy ion collsions, we highlight: 1) recent measurements of strange hadrons and heavy flavor decay electrons up to high $p_T$ to study jet interaction with the medium and explore partonic energy loss mechanisms; and 2) $\Upsilon$ and high $p_T$ $J/\psi$ measurements to study the effect of color screening and other possible production mechanisms.

## 1. Introduction

The physics goal at RHIC is to study and identify the properties of matter with partonic degrees of freedom [1]. Hard probes such as identified particles at high $p_T$, heavy flavor and jets are thought to be well calibrated probes since they are calculable in the perturbative Quantum Chromodynamics (pQCD) framework [2]. The single inclusive hadron production in p+p collisions at $p_T > 2$ GeV/$c$ is described by the convolution of parton distribution functions, parton-parton interaction cross sections and fragmentation functions (FFs). In Au+Au collisions, particle production at $p_T > 6$ GeV/$c$ can be described by the fragmentation process with jet energy loss. When jets traverse the hot and dense medium, they lose energy through gluon radiation and/or colliding elastically with surrounding partons [3, 4, 5]. This leads to a softening of hadron spectra at high $p_T$. The softening can be characterized through nuclear modification factor ($R_{AA}$ ($R_{CP}$)), the spectrum in central Au+Au collisions divided by that in p+p (peripheral Au+Au) collisions, scaled by the number of underlying binary nucleon-nucleon inelastic collisions ($N_{bin}$). The amount of energy loss can be calculated in QCD and is expected to be different for light quarks, gluons and heavy quarks [6, 7]. Through the comparison between $R_{AA}$ or $R_{CP}$ measurements

with theoretical calculations, medium properties such as gluon density and transport coefficient can be derived.

To further understand energy loss mechanisms and medium properties, we measured nuclear modification factors for protons, pions and non-photonic electrons at STAR to test color charge and flavor dependence of energy loss. For example, gluons carry different Casmir factor from quarks. The coupling of the gluon to the medium is stronger than the coupling of quark to medium thus gluons are expected to lose more energy than quarks when traversing the medium. At RHIC energy, gluon jet contribution to protons is expected to be significantly larger than to pions at high $p_T$ [6, 8, 9], therefore, protons are expected to be more suppressed than pions in $R_{AA}$ or $R_{CP}$ measurement. Experimentally, protons and pions show similar magnitudes of suppression in $R_{CP}$ [10], which is contradictory to the color charge dependence of energy loss picture. Intrigued by our data, several calculations are proposed. One of those is jet conversion mechanism [11], in which, jet can change flavor or color charge after interaction with the medium. Including both jet energy loss and conversion in the expanding medium, the calculation results in a net quark to gluon jet conversion. This leads to a better agreement with data. With a much larger jet conversion cross section compared to that in the Leading Order calculation, the proton and pion suppression magnitudes are similar. The same idea are used to predict strange hadron $R_{AA}$. Using the same factor scaling the leading order (LO) QCD calculations, kaons are predicted to be less suppressed with jet conversion than pions since the initially produced hard strange quarks are much fewer than the strange quarks in a hot, dense medium [12]. The interaction between the initially produced light quark (gluon) and the medium will lead to more strangeness production at high $p_T$ at RHIC energies compared to the case without jet conversion. Alternatively, enhanced parton splitting in the medium will also lead to a change of the jet hadron chemical composition in Au+Au collisions compared to that in p+p collisions [13]. On the other hand, non-photonic electrons, which are from heavy flavor charm and bottom decay, show a similar magnitude of suppression as light hadrons [14]. The pQCD calculations including collisional and radiative energy loss show a systematically higher $R_{AA}$ value than experimental data [15, 16]. Further calculations indicate that with charm contribution only, non-photonic electrons are expected to reproduce the data [16]. In this proceedings, recent results on strange hadron and heavy flavor at high $p_T$ from STAR are presented to further understand energy loss mechanisms in the medium.

## 2. Strange hadron measurements in p+p and Au+Au collisions

### *2.1. Constrain Fragmentation Functions (FFs)*

To understand the medium properties using hard probes, it is necessary to understand particle production in p+p collisions. Using STAR Barrel Electron-magnetic Calorimeter (BEMC) triggered events, identified particles such as $\pi^{\pm}$, $K^{\pm}$, $p(\bar{p})$, $K^0_S$

and $\rho^0$ can be measured up to $p_T = 15$ GeV/$c$ in p+p collisions at $\sqrt{s_{NN}} = 200$ GeV at mid-rapidity $|y| < 0.5$. Figure 1 (left) shows the $K/\pi$ ratios measured in 200 GeV p+p collisions together with those from next-to-leading order (NLO) pQCD calculations with different FFs. In the overlapping $p_T$ region, the spectra of $K^{\pm}$ and $K_S^0$ are consistent. The NLO pQCD calculations with AKK [8] and DSS [17] FFs do not reproduce the $K/\pi$ ratio while the LO PYTHIA calculations lead to a better agreement with data. Not shown in this figure, but shown in [18], the NLO pQCD calculations with AKK and DSS FFs can not reproduce the $p(\bar{p})/\pi$ ratios at high $p_T$ either while the LO PYTHIA calculations lead to a better agreement with data also. The identified particle spectra measurements of $\pi^{\pm}$, $K$ and $p(\bar{p})$ at STAR should be able to further constrain light flavor separated FFs and gluon FFs.

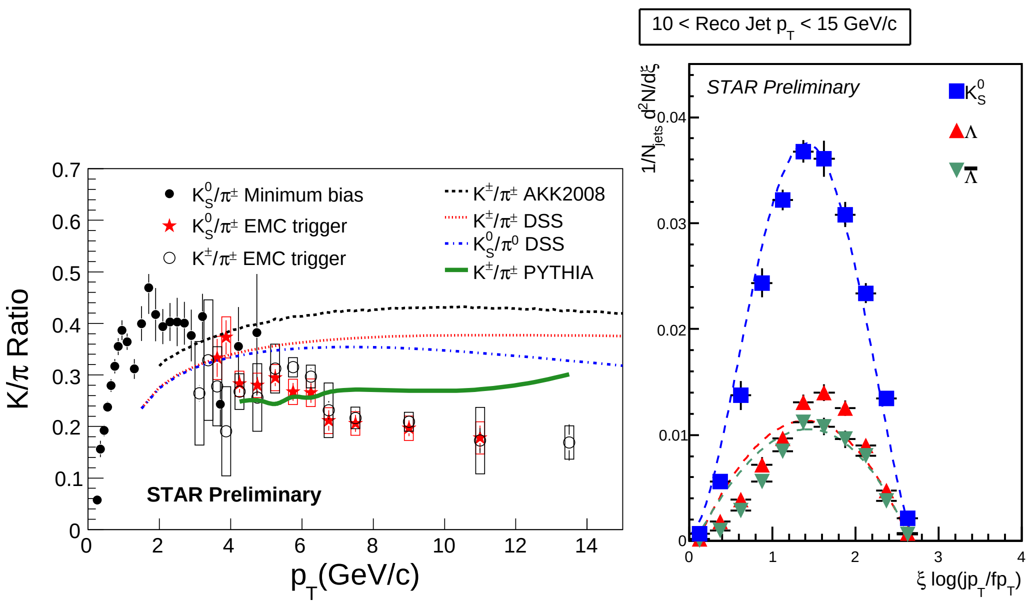


**Figure 1.** (in color on line) (left) The $K/\pi$ ratios in p+p collisions at 200 GeV. Shown as different lines are calculations from NLO pQCD calculations with AKK and DSS FFs and LO PYTHIA calculations. (right) The FF measurements for $K_S^0$, $\Lambda$ and $\bar{\Lambda}$ in 200 GeV p+p collisions. Also shown are those from PYTHIA calculations as dashed lines. The double counting correction was done while missing energy, energy resolution and tracking efficiency have not been corrected for.

Taking advantage of the large acceptance of the STAR TPC, we can measure the FFs of identified particles directly. Shown in Fig. 1 (right) are the FF measurements for $K_S^0$, $\Lambda$ and $\bar{\Lambda}$ in 200 GeV p+p collisions with jet energy of $10 < p_T < 15$ GeV/$c$. The details of the analysis can be found at [19]. Interestingly, PYTHIA can reproduce the $K_S^0$ FF reasonably well but shows deviation from $\Lambda$ and $\bar{\Lambda}$ FF measurements.

### *2.2. Jet hadro-chemistry change from p+p to Au+Au collisions*

Figure 2 (left) shows the $K^{\pm}(K_S^0)/\pi^{\pm}$ ratios as a function of $p_T$ in p+p and 0-12% central Au+Au collisions. At $p_T > 6$ GeV/$c$, the $K/\pi$ ratio in central Au+Au

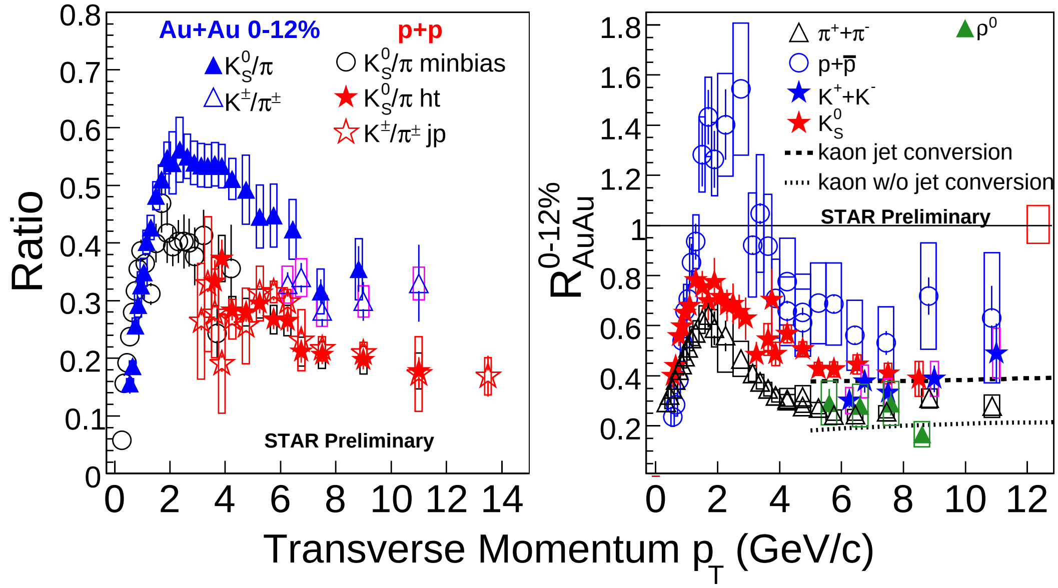


**Figure 2.** (left) The $K^{\pm}(K_S^0)/\pi^{\pm}$ ratios as a function of $p_T$ in p+p and 0-12% central Au+Au collisions. (right) Nuclear modification factors of $\pi$, K, $p(\bar{p})$ and $\rho$ in Au+Au collisions. The bars and boxes represent statistical and systematic uncertainties.

collisions is higher than that in p+p collisions, indicating that the jet hadro-chemistry change from elementary p+p to central Au+Au collisions. Figure 2 (right) shows nuclear modification factors of $\pi$, K, $p(\bar{p})$ and $\rho$ in Au+Au collisions. The $\pi^+ + \pi^-$ and $p + \bar{p}$ spectra in central Au+Au collisions are from ref. [10]. We observe that $R_{AA}(K^+ + K^-, K_S^0)$ is larger than $R_{AA}(\pi^+ + \pi^-)$. This is consistent with the prediction of jet conversion in the hot dense medium, as shown by the dashed line, the prediction presented in ref. [12]. However, using the same parameters this jet conversion scenario predicts similar $R_{AA}$ for protons and pions [11], while experimentally we observe $R_{AA}(p + \bar{p})$ seems to be larger than $R_{AA}(\pi^+ + \pi^-)$. The full systematic uncertainties for protons are under study. Recently, it was argued that a higher twisted effect, enhanced parton splitting, can alone lead to significant changes in the jet hadron chemical composition [13]. In this model, heavier hadrons become more abundant relative to the case without enhanced parton splitting mechanism. For a jet with 50 GeV of energy, the kaon to pion ratio increases by a factor $\sim$ 50% and the proton to pion ratio by a factor $\sim$ 100% [13]. Together with the jet conversion mechanism, this might be able to explain our observations. However, a full comparison requires consideration of quantitative modelling and calculations incorporating 3D hydro in an expanding medium [20] and proper light flavor-separated quark and gluon fragmentation functions. Experimentally, high $p_T$ strange hadron measurements in d+Au, its centrality dependence of $R_{AA}$ in Au+Au and elliptic flow $v_2$ measurements will shed more light on our understanding of energy loss mechanisms.

## 3. Heavy flavor measurements

### *3.1. e-h correlation to access B contribution to non-photonic electrons in p+p*

Using the azimuthal angle correlations between non-photonic electrons and charged hadrons (e-h) and between non-photonic electrons and $D^0$ ($e - D^0$), we measured bottom contribution factor to non-photonic electrons [21]. It was found that at $p_T > 5$ GeV/$c$, bottom contribution is about 50%. This together with non-photonic electron $R_{AA}$ measurements still challenge the pQCD energy loss model calculations, indicating that collisional dissociation of heavy mesons [22], in-medium heavy resonance diffusion [23], and multi-body mechanisms [24] might play an important role for heavy quark interaction with the medium. Due to the large systematic uncertainty of the current non-photonic electron measurements, it is not yet possible to distinguish different mechanisms mentioned above and/or determine their possible relative contributions. In the future, measurements on direct topological reconstruction of heavy favor hadron decays are crucial to understand precisely the energy loss of heavy flavor [25].

### *3.2. high $p_T$ $J/\psi$ measurements in p+p and A+A collisions*

The dissociation of quarkonia due to color screening in a Quark-Gluon Plasma (QGP) is thought to be a classic signature of de-confinement in relativistic heavy-ion collisions [26]. Results at RHIC show that the suppression of the $J/\psi$ as a function of centrality (the number of participants) is similar to that observed at the SPS, even though the energy density reached in collisions at RHIC is significantly higher [27, 28]. Possible mechanisms such as sequential suppression [29], $c\bar{c}$ recombination [30, 31, 32, 33] were proposed to explain this. Recent Lattice QCD calculations indicate that direct $J/\psi$ is not dissociated in the medium created at RHIC while the suppression observed for $J/\psi$ comes from the dissociation of $\chi_c$ and $\psi'$ [34]. However, the direct $J/\psi$ might be dissociated at RHIC at high $p_T$, which was predicted in the hot wind dissociation picture, in which the AdS/CFT approach was used and the dissociation temperature for $J/\psi$ was predicted to decrease as a function of $p_T$ [35]. The AdS/CFT approach was applied to hydro framework and predicted that $J/\psi$ $R_{AA}$ decreases versus $p_T$ [36].

Figure 3 shows $J/\psi$ $R_{AA}$ as a function of $p_T$ in 0-20% and 0-60% Cu+Cu collisions from STAR [37] and 0-20% Cu+Cu collisions from PHENIX [38]. The average of two STAR 0-20% data points at high $p_T$ is $R_{AA} = 1.4 \pm 0.4(stat.) \pm 0.2(syst.)$. Compared to low $p_T$ PHENIX measurements, our results indicate that $R_{AA}$ of $J/\psi$ increases from low $p_T$ to high $p_T$ at 97% confidence level (C.L.). The $R_{AA}$ of high $p_T$ $J/\psi$ is in contrast to strong suppression for open charm [15, 22, 39], indicating that $J/\psi$ might be dominantly produced through color singlet configuration. However, even though there is significant improvement from the next-next-to-leading order (NNLO) pQCD calculations with color singlet model, the calculation still fails to reproduce the high $p_T$ part [40]. The $R_{AA}$ trend of $J/\psi$ is contradictory to AdS/CFT+hydrodynamic calculations at 99% C.L.. This might indicate two things: 1) Cu+Cu system is not big enough so that the calculation

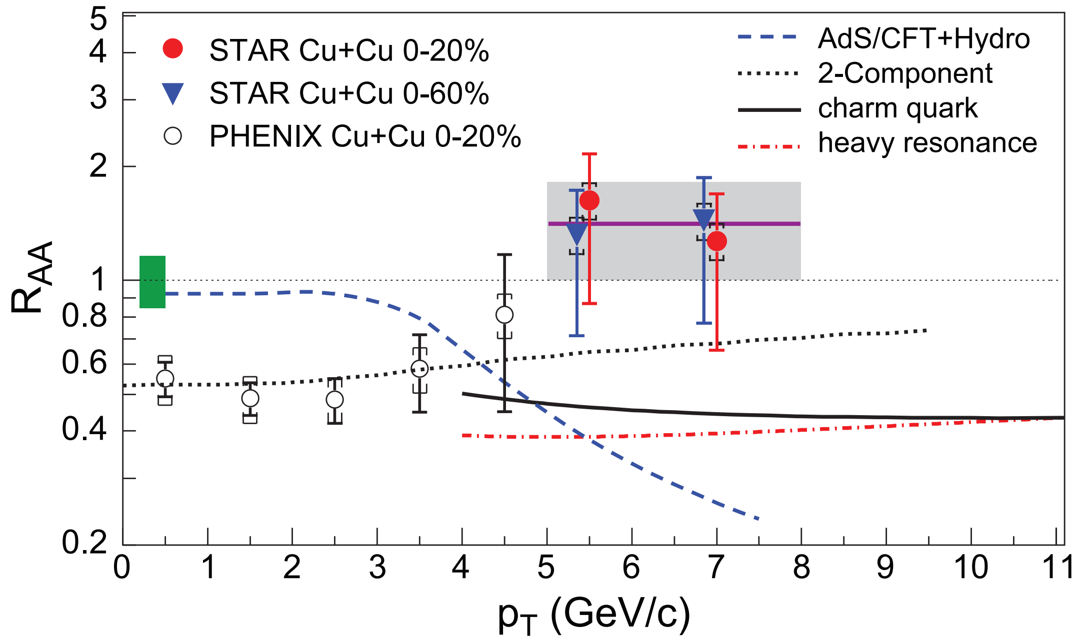


**Figure 3.** $J/\psi$ $R_{AA}$ versus $p_T$. STAR data points have statistical (bars) and systematic (caps) uncertainties. The box about unity on the left shows $R_{AA}$ normalization uncertainty, which is the quadrature sum of p+p normalization and binary collision scaling uncertainties. The solid line and band show the average and uncertainty of the two 0-20% data points. The curves are model calculations described in the text. The uncertainty band of 10% for the dotted curve is not shown.

is not applicable. The larger system produced in Au+Au collisions may be necessary to observe or exclude the effect predicted by AdS/CFT; 2) the formation time effect for high $p_T$ $J/\psi$ is important since the AdS/CFT+hydrodynamic calculation shown in Fig. 3 requires that the $J/\psi$ be produced as an on-shell $J/\psi$ fermion pair almost instantaneously at the initial impact with no formation time. A calculation combining effects of $J/\psi$ formation time, color screening, hadronic phase dissociation, statistical $c\bar{c}$ coalescence and B meson feed-down contribution can describe the data [41]. The calculation suggests a slight increase in the $R_{AA}$ at higher $p_T$.

The excellent signal over background ratio of high $p_T$ $J/\psi$ enables to do two particle azimuthal angle correlations between $J/\psi$ and charged hadrons ($J/\psi - h$) in p+p collisions. From $J/\psi - h$ correlations, B meson contribution to inclusive $J/\psi$ is obtained to be 13±5% [37]. Even though there is no direct measurement of B meson at RHIC, indirect measurements can help to constrain B cross section in pQCD calculations through $J/\psi$–$h$ and $e_{non-photonic} - h$ correlations, which constrain B contribution factor to inclusive $J/\psi$ and non-photonic electron yield respectively.

### *3.3.* $\Upsilon$ *measurements at STAR*

Besides $J/\psi$, the $\Upsilon$ states are also ideal tools to study the effect of color screening in hot and dense QCD matter since its ground states and excited states melt at different

temperatures and all of them decay to dileptons [29]. Furthermore, since the $b\bar{b}$ cross section at RHIC energy is expected to be much smaller compared to $c\bar{c}$ cross section from FONLL calculations [42], the recombination contribution from QGP phase might be negligible to bottomonia production. This makes the $\Upsilon$ even a better probe for studying the color screening effect in QGP if sufficient statistics can be achieved experimentally. STAR has measured $\Upsilon \rightarrow e^+e^-$ in p+p, d+Au and Au+Au collisions [43]. The low material from run 8 significantly reduced the background for $\Upsilon \rightarrow e^+e^-$ measurement. The $\Upsilon$ $R_{dAu} = 0.98 \pm 0.32(stat.) \pm 0.28(syst.)$, indicating that $\Upsilon$ production follows $N_{bin}$ scaling in d+Au collisions.

### *3.4. Further measurements of heavy flavor*

To further understand the production mechanisms of quarkonia at high $p_T$ and medium properties, STAR will measure the following: nuclear modification factors of $J/\psi$ from low to high $p_T$ in Au+Au and d+Au collisions, $J/\psi$ $v_2$, forward and backward $J/\psi$ to address intrinsic charm contribution at large $x_F$ [44], $J/\psi - h$ correlations to access contribution factor from B, spin alignment of $J/\psi$, higher charmonia states and different $\Upsilon$ states. The muons in $\Upsilon \rightarrow \mu^+\mu^-$ do not suffer from Bremsstrahlung radiation and with the Muon Telescope Detector upgrade, we can cleanly separate the ground state from the excited states even with the upgraded inner tracker with additional material in the future [45].

## 4. Summary

We report $K^{\pm}$ $p_T$ spectra at mid-rapidity ($|y| < 0.5$) up to 15 GeV/$c$, and neutral Kaon ($K^0_S$) $p_T$ spectra up to 12 GeV/$c$ using events triggered by the STAR BEMC from p+p collisions at $\sqrt{s_{NN}} = 200$ GeV. In p+p collisions, the calculations from NLO pQCD models, fail to reproduce the $K^{\pm}$ spectra at high $p_T$. At $p_T > 6$ GeV/$c$, we observe $R_{AA}(K^0_S, K^{\pm}, p + \bar{p}) > R_{AA}(\pi^+ + \pi^-) \sim R_{AA}(\rho^0) \sim R_{AA}(e_{non-photonic})$. This challenges pQCD energy loss model calculations. High $p_T$ $J/\psi$ invariant cross sections in p+p and Cu+Cu collisions were measured up to 14 GeV/$c$. The $R_{AA}$ of $J/\psi$ at $p_T > 5$ GeV/$c$ is consistent with unity. These measurements together with $\Upsilon$ results can further help to understand quarkonia production mechanisms and medium properties. In the future, STAR heavy flavor measurement will significantly benefit from detector upgrade of Heavy Flavor Tracker [25] and possible Muon Telescope Detector [45].

## References

[1] J. Adams *et al.* (STAR Collaboration), Nucl. Phys. A **757**, 102 (2005).
[2] J.C. Collins, D.E. Soper, Annu. Rev. Nucl. Part. Sci. 37 (1987) 383; J.C. Collins, D.E. soper, G. Sterman, Adv. Ser. Direct. High Energy Phys. 5 (1988) 1.
[3] M. Gyulassy *et al.*, nucl-th/0302077; A. Kovner *et al.*, hep-ph/0304151, Review for: Quark Gluon Plasma 3, Editors: R.C. Hwa and X.N. Wang, World Scientific, Singapore.
[4] J. Adams *et al.*, Phys. Rev. Lett. **91**, 172302 (2003).

[5] S.S. Adler *et al.*, Phys. Rev. Lett. **91**, 072301 (2003); S.S. Adler *et al.*, Phys. Rev. Lett. **91**, 241803 (2003); B.B. Back *et al.*, Phys. Lett. B **578**, 297 (2004); I. Arsene *et al.*, Phys. Rev. Lett. **91**, 072305 (2003).
[6] X.N. Wang, Phys. Rev. C **58**, 2321 (1998).
[7] Y. Dokshitzer *et al.*, Phys. Lett. B **519**, 199 (2001).
[8] S. Albino *et al.*, Nucl. Phys. B **725**, 181 (2005).
[9] J. Adams *et al.*, Phys. Lett. B **616**, 8 (2005); J. Adams *et al.*, Phys. Lett. B **637**, 161 (2006).
[10] STAR collaboration, B.I. Abelev *et al.*, Phys. Rev. Lett. 97 (2006) 152301; B.I. Abelev *et al.*, Phys. Lett. B 655, 104 (2007).
[11] W. Liu, C.M. Ko, B.W. Zhang, Phys. Rev. C 75, 051901 (2007).
[12] W. Liu and R.L. Fries, Phys. Rev. C 77, 054902 (2008).
[13] S. Sapeta and U.A. Wiedemann, Eur. Phys. J. C **55**, 293 (2008), arXiv:0707.3494.
[14] J. Adams *et al.*, Phys. Rev. Lett. **94**, 62301 (2005); B.I. Abelev *et al.*, Phys. Rev. Lett. **98**, 192301 (2007).
[15] S. Wicks *et al.*, Nucl. Phys. A **784**, 426 (2007).
[16] N. Armesto et al., Phys. Lett. B **637**, 362 (2006).
[17] D. d. Florian, R. Sassot and M. Stratmann arXiv: 0707.1506, Phys. Rev. D 76(2007) 074033.
[18] Y. Xu *et al.* (STAR Collaboration), these proceedings.
[19] A. Timmins *et al.* (STAR Collaboration), these proceedings.
[20] T. Renk and K. Eskola, Phys. Rev. C **76**, 027901 (2007).
[21] B. Biritz *et al.* (STAR Collaboration), Nucl. Phys. A **830**, 849C (2009).
[22] A. Adil and I. Vitev, Phys. Lett. B **649**, 139 (2007).
[23] H. v. Hess, V. Greco and R. Rapp, Phys. Rev. C **73**, 034913 (2006).
[24] W. Liu and C. M. Ko, nucl-th/0603004.
[25] STAR Heavy Flavor Tracker proposal, http://rnc.lbl.gov/hft/docs/hft_final_submission_version.pdf; S. Kleinfelder *et al.*, Nucl. Instr. Meth. A **565**, 132 (2006).
[26] T. Matsui and H. Satz, Phys. Lett. B **178**, 416 (1986).
[27] A. Adare *et al.*, Phys. Rev. Lett. **98**, 232301 (2007).
[28] M. C. Abreu *et al.*, Phys. Lett. B **499**, 85 (2001).
[29] H. Satz, J. Phys. G **32**, R25 (2006); F. Karsch, D. Kharzeev and H. Satz, Phys. Lett. B **637**, 75 (2006).
[30] P. Braun-Munzinger and J. Stachel, Phys. Lett. B **490**, 196 (2000).
[31] L. Grandchamp and R. Rapp, Phys. Lett. B **523**, 60 (2001).
[32] M. I. Gorenstein *et al.*, Phys. Lett. B **524**, 265 (2002).
[33] R. L. Thews, M. Schroedter and J. Rafelski, Phys. Rev. C **63**, 054905 (2001).
[34] M. Asakawa *et al.*, Prog. Part. Nucl. Phys. 46, 459 (2001); M. Asakawa and T. Hatsuda, Phys. Rev. Lett. 92, 012001 (2004); S. Datta *et al.*, Phys. Rev. D 69, 094507 (2004).
[35] H. Liu, K. Rajagopal and U.A. Wiedemann, Phys. Rev. Lett. **98**, 182301 (2007).
[36] T. Gunji *et al.*, J. Phys. G **35**, 104137 (2008).
[37] B.I. Abelev *et al.*, Phys. Rev. C **80**, 041902 (2009), arXiv:0904.0439; Z. Tang, Ph.D. thesis, University of Science and Technology of China, 2009.
[38] A. Adare *et al.*, Phys. Rev. Lett. **101**, 122301 (2008).
[39] W.A. Horowitz private communication; I. Vitev private communication.
[40] P. Artoisenet et al., Phys. Rev. Lett. 101, 152001 (2008), and J.P. Lansberg private communication.
[41] X. Zhao and R. Rapp, Phys. Lett. B **664**, 253 (2008).
[42] R. Vogt, M. Cacciari and P. Nason, Nucl. Phys. A 774, 661, 2006.
[43] R. Reed *et al.* (STAR Collaboration), these proceedings.
[44] C. Perkins *et al.* (STAR Collaboration), Nucl. Phys. A **830**, 231C (2009).
[45] Z. Xu, BNL LDRD project 07-007; L. Ruan *et al.*, J. Phys. G **36**, 095001 (2009).